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Summary

The NASA Lewis Research Center has designed, fabricated and installed two photovoltaic power systems in remote villages in the United States and Africa. These projects were undertaken to demonstrate that existing photovoltaic system technology is capable of providing electrical power for basic domestic services for the millions of small, remote communities in both developed and developing countries.

One system is located in the Papago Indian Village of Schuchuli in southwest Arizona (U.S.A.) and became operational 16 December 1978. The other system is located in Tangaye, a rural village in Upper Volta, Africa. It became operational 1 March 1979.

The Schuchuli system has a 3.5 kW (peak) solar array which provides electric power for village water pumping, a refrigerator for each family, lights in the village buildings, and a community washing machine and sewing machine. The 1.8 kW (peak) Tangaye system provides power for community water pumping, flour milling and lights in the milling building.

These are both stand-alone systems (i.e., no back-up power source) which are being operated and maintained by local personnel. Both systems are instrumented. Systems operations are being monitored by NASA to measure design adequacy and to refine designs for future systems. Baseline socioeconomic studies have been performed for both villages. Follow-up studies are planned to determine the impact of the power systems on the villagers.

This paper describes the designs, hardware, and installations for both systems.

1. INTRODUCTION

On 16 December, 1978, Schuchuli, Arizona, became the first village in the world to obtain all of its electricity from the photovoltaic (PV) conversion of solar energy. Schuchuli is a small village on the western edge of the 1 113 360 hectare Papago Indian Reservation in southwestern Arizona. The village's 15 families (95 people) are 27 km from the nearest available electric utility power. Before installation of the PV power system, their choice of foods was restricted because of lack of refrigeration. Cattle, which they raise, and game provided sources of meat, but these had to be consumed quickly or preserved by drying. Water was provided by a diesel-powered pump, and kerosene lamps and candles provided lighting in the homes. The principal objective of this project is to demonstrate the feasibility of a village PV power system. This project is funded by the U.S. Department of Energy, implemented by the NASA Lewis Research Center (LeRC), and carried out with the cooperation of the U.S. Public Health Service and the Papago Tribe of Arizona.

On 1 March 1979, Tangaye, Upper Volta, became the first village in a developing country to have a water pump and flour mill powered by electricity from a PV power system. Tangaye is a village of about 2200 people and is located about 190 km east of Ouagadougou, Upper Volta. The people live in a subsistence level agricultural economy. Millet, sorghum, maize, peanuts and cotton are the principal crops. A variety of vegetables are grown and cattle, sheep, goats and fowl are raised. The objectives of this project are to study the social and economic effects of relieving women of the 1 to 2 hour per day chore of hand milling flour and hand lifting water from wells and to demonstrate PV as a renewable energy resource in a developing country. The project is being implemented by the NASA/LeRC for the U.S. Agency for International Development (U.S. AID) as part of AID's project "Studies of Energy Needs in the Food System."

2. SYSTEMS DESCRIPTIONS

The Schuchuli and Tangaye systems are depicted in figures 1 and 2. Both systems consist of a PV array, batteries, controls and instrumentation, power distribution, and loads. The PV arrays, batteries, and loads for both systems operate at 120 volts DC. Controls and instrumentation for both systems operate at 12 V DC. Use of DC systems avoids the costs, complexities, and losses associated with DC-AC inverters while 120 volts mini-

mizes line losses and permits the use of commercially available DC switches and motors. All electrical load devices were individually selected on the basis of energy efficiency. PV array and battery sizes were determined using a NASA/LeRC-developed computerized PV system simulation program. The program combines PV cell characteristics, average monthly insolation and atmospheric data, and an hourly load profile to determine hourly battery depth-of-discharge (DOD) as a function of array size and tilt angle, and battery capacity. It also incorporates a factor for module output losses due to dirt and encapsulant darkening and a subroutine to randomly vary insolation within selected limits to develop worst-case DOD conditions.

The 3.5 kW (peak) Schuchuli PV array consists of twenty-four 1.22 by 2.44 m panels each containing eight modules connected in series to form a 120 volt string. The panels are designed for 160 km/h winds and are bolted together from commercially available steel channels and hardware. There are three rows of eight panels each mounted to steel uprights set in concrete piers. The rows are stepped to minimize interrow spacing while eliminating low sun angle shadowing. The 1.8 kW (peak) Tangaye array contains twelve similar panels arranged in three rows of four. The Tangaye panels are mounted to triangular structures whose base legs are buried and anchored about 0.3 m below grade. This design eliminates the need for concrete and minimizes excavation. The Schuchuli array tilt angle is changed four times a year (48°, 26°, 3.5°, 26°) to maximize array output. The insolation characteristics at Tangaye (lat., 13°) allow nearly maximum array output at a single tilt angle (11°).

The main (120 V) battery of the Schuchuli system has a 2380 ampere-hour (Ah) capacity and the instrumentation and control (I/C) battery has a 1055 Ah capacity. The I/C battery is charged from the 120 V system through a DC/DC converter. Calculated worst-case DOD for the main battery is 60%. Main battery capacity of the Tangaye system is 540 Ah and the I/C battery capacity is 200 Ah. The Tangaye I/C battery is charged from a separate 12 V, 74 W PV array. Calculated worst-case DOD for the main battery is 30%. At Schuchuli, the batteries are installed in a vented room in the Electrical Equipment Building (EEB). At Tangaye, they are in a vented room in the Mill/Battery Building.

Both systems use lead-calcium grid battery cells specifically designed for deep cycling operation. Lead-calcium cells were selected for low gas

evolution, low self-discharge, high charge efficiency, and constant charge voltage over the lifetime of the cell.

For both the Schuchuli and Tangaye systems, system voltage regulation and battery charge control is accomplished by array string switching. Each series string in the array is connected to the main bus through a relay. A controller senses system voltage and commands a programmable drum relay to disconnect (open circuit) or connect series strings to keep system voltage at or below the maximum safe battery charge voltage. Over- and under-voltage protection is also provided. If system voltage exceeds a maximum allowable value, the PV array is disconnected. If system voltage drops below a minimum allowable value, the loads are disconnected. Alarm lights are provided to indicate these conditions.

The Schuchuli system powers five types of loads: the village water pump; lights in all the buildings; and refrigerators, a sewing machine, and a washing machine installed in a Domestic Services Building (DSB). A 2 hp, 120 V DC permanent magnet motor drives the positive displacement jack-type water pump. It delivers approximately 4.2 m^3/h to the village water distribution system, which includes a 41.6 m^3 storage tank located 365 m from the well. Water requirements were forecast to vary from 7.6 m^3/day in winter to 18.9 m^3/day in summer. The water system and pump had been previously installed by the U.S. Public Health Service. Motor operation is controlled by level sensors in the tank and a PV array output sensor to operate during periods of 20% or greater array output during periods of normal insolation and water demand. During extended cloudy weather or exceptionally heavy demand, secondary controls start the motor regardless of array output.

A total of fifty-three 20 watt, 120 V DC fluorescent lights are installed in the village. There are two lights in each house, four in the church, seven in the feast house, two in the DSB, and four in the EEB. The lights use commercially available high efficiency 120 V DC, 23 kHz inverter-ballasts which enable a standard 20 W lamp to produce the same lumen output as when powered by a 120 V AC, 60 Hz ballast.

A total of fifteen 0.13 m^3 refrigerators (each having a small freezer compartment) are installed in a locker-type arrangement in the DSB. These refrigerators are a custom-design developed by a manufacturer of marine refrigerators and are completely insulated with a minimum of 7.6 cm of

polyurethane foam. Each unit has an automatic door closer and a key lock. Three refrigerators are assembled in a single cabinet and manifolded to a single compressor having a 1/8 hp, 120 V DC permanent magnet motor. A unique energy-saving feature of the refrigerator design is the cold wall. Instead of the conventional fin and tube evaporator, the evaporator coils are contained in two enclosed trays containing a gel coolant mixture. The refrigerant freezes the mixture, which then acts as an ice bank to keep the freezer compartment at about -18 C and the refrigerator compartment at about 3.5 C. Manufacturer tests on similar units indicate compressor "on" time should be about 25% in a 43 C ambient environment. To further enhance refrigerator efficiency, the compressors are located in a vented enclosure outside the DSB so that waste heat is rejected to the outdoors rather than to the room containing the refrigerators.

A standard wringer-type washer was refitted with a 1/4 hp, 120 V DC permanent magnet motor. A wringer-type washer was selected for overall simplicity, to minimize water consumption, and because the women prefer that type washer. The washer is connected to a timer which allows up to 12 hours per day cumulative washer operating time, or 1.75 loads per person per week at 1/2 hour per load.

A commercially available sewing machine having a 1/8 hp, 120 V universal motor was also installed in the DSB.

Because of a number of uncertainties regarding load usage at Schuchuli, a load management system is utilized to protect the battery from excessive discharge and to maintain operation of critical loads at the expense of less critical loads. Battery DOD is used to trigger sequential load shedding. Battery DOD is determined by sensing end-of-discharge voltage of four pilot cells which during discharge are sequentially connected in series with the main battery cells. One pilot cell has a 1055 Ah capacity and the other three each has a 310 Ah capacity. Together the pilot cells represent 80% capacity of the main battery in 50, 10, 10, and 10% increments. At 50% DOD the washing and sewing machines are disconnected; at 60% DOD village lights are disconnected; at 70% DOD the water pump is disconnected; and at 80% the refrigerators are disconnected. The pilot cells are recharged and the associated loads are reconnected in the reverse sequence. During normal operation, i.e., when the main battery is fully charged, all four pilot cells are connected in parallel and together act as an additional series cell. Pilot cell sequencing and load shedding/

reconnecting are accomplished by the programmable drum relay.

The Tangaye system contains three loads: the water pump, the flour mill, and the lights located in a Mill/Battery Building. System size (i.e., array peak power and battery capacity), mill size, and mill operating time per day were based on limitations of available funds. Water pumping was assumed to be limited by the 5 m^3/day measured yield of the well.

A 1/4 hp, 120 V DC permanent magnet motor drives a positive displacement jack-type pump which can deliver 1.5 m^3/h from the shallow (10.7 m deep) well to a 6 m^3 water storage tank. The water tank has five faucets attached to a pipe located along its side. The pump motor is controlled by water level sensors in the tank and in the bottom of the well since pumping is limited by well yield.

A 1 hp, 120 V DC permanent magnet motor drives the flour mill. A timer allows the mill to operate up to a cumulative total of 8 h/day. The mill, a burr type, is capable of grinding about 40 kg/h of fine-ground flour, or 320 kg/8-h day, which is enough for about 640 people per day. Two 20 W fluorescent lamps (identical to those used at Schuchuli) are located in the milling room.

Both the Schuchuli and Tangaye systems are completely instrumented. Each has a complete set of panel meters and an automatic cassette-type data logger, which records all system parameters once per hour. The panel meters are read daily by designated individuals in each village. Data are forwarded to LeRC weekly from Schuchuli and approximately bi-weekly from Tangaye.

Baseline socio-economic studies have been completed in both villages. Quarterly reviews are being conducted of the socio-economic status of Schuchuli with a final in-depth study to be performed at the end of a year of system operation. Socio-economic changes at Tangaye will be monitored by U.S. AID personnel with a final in-depth study also to be performed at the end of a year of system operation.

A groupment (co-op) consisting of about 60 village families has been formed to manage the milling operation. The membership fee is 500 Fr CFA . Charges for milling are set by the groupment and are competitive with mills in nearby villages. Milling is open to member and nonmember families alike. Proceeds from membership and milling are used to pay two full-time

millers and to accumulate funds for spare parts and repairs after the first year of operation. Once adequate funds are established, profits will be distributed to groupment members.

3. SYSTEMS INSTALLATION AND OPERATION

Total on-site installation time for the Schuchuli system was 3-1/2 months. Installation of system hardware, construction of the EEB and DSB, and wiring of the homes and community buildings were accomplished by the Papago Construction Company. An overhead power distribution system was installed by the Papago Tribal Utility Authority. LeRC personnel supervised installation and performed system checkout.

The system is designed for automatic operation. A villager has been designated Power System Manager and has been trained to recognize and report problems to LeRC, take panel meter data, replace the data logger cassette, and perform routine maintenance. Routine maintenance consists of changing array tilt angle, washing the array, maintaining battery electrolyte levels, and maintenance of the loads.

Total on-site installation time for the Tangaye system was 6 weeks, exclusive of the time required for the villagers to build the mud-brick Milling/Battery Building. U.S. AID procured the water tank in Ouagadougou, installed the tank, and supervised building construction. Two LeRC personnel, with the help of villagers, installed the PV system and loads. Water pumping began 4 weeks after start of installation and milling began 2 weeks later.

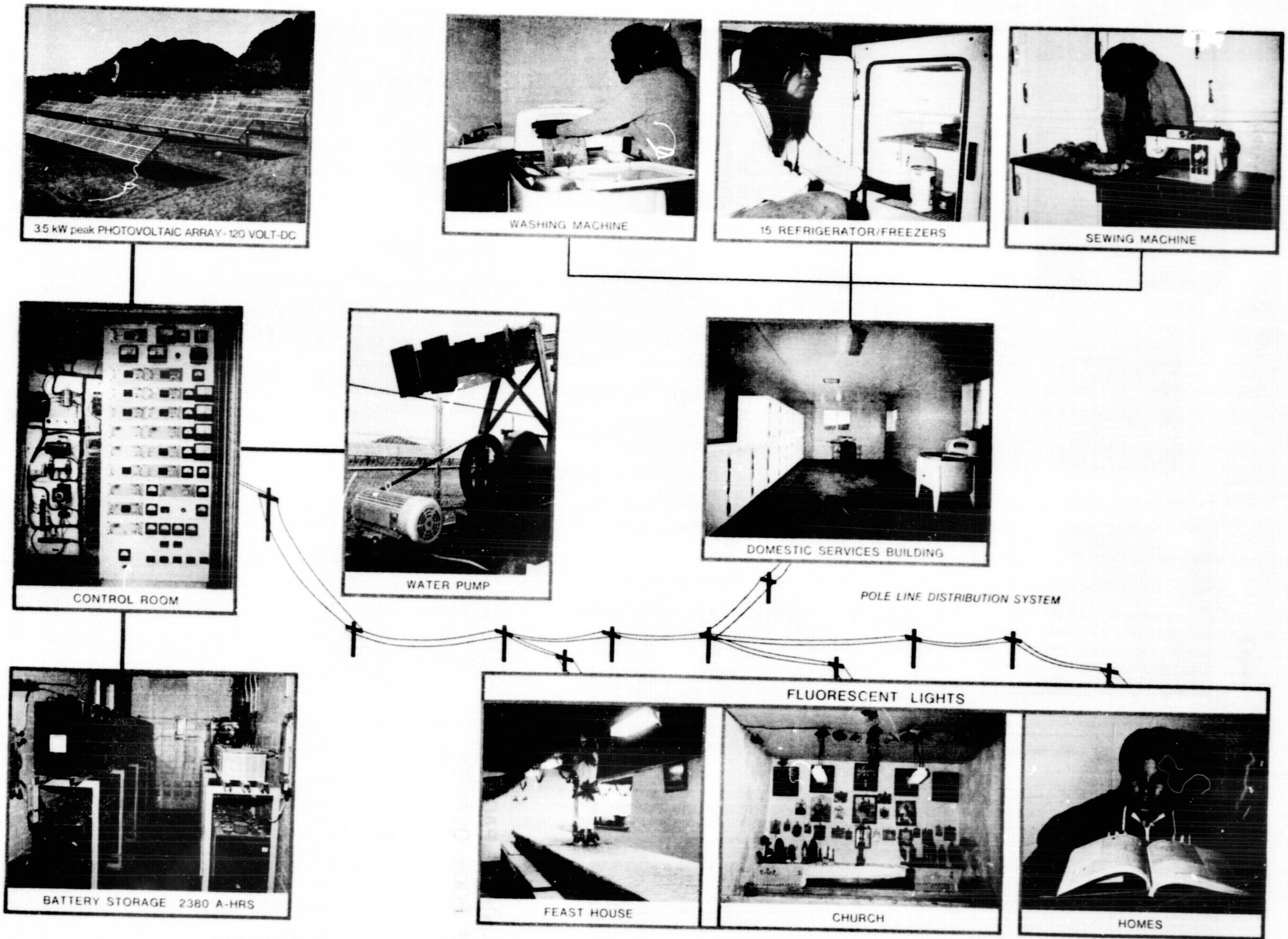
4. CONCLUDING REMARKS

The Schuchuli system has been operating satisfactorily since 16 December 1978. Water pumping has been about one-half that planned for this time of year because of the unusually cold and wet weather and because the women in the village are only gradually beginning to use the washing machine. The people were most grateful for lights in their homes and are gradually changing their food buying habits to use more refrigerated foodstuffs.

The Tangaye system has been operating since 1 March 1979. Running water has been extremely popular with the villagers and the water pumping rate has reached an astonishing 13.6 m^3/day. This is about twice the yield of 10-12 m deep wells in the Tangaye area. Groupment members plus non-

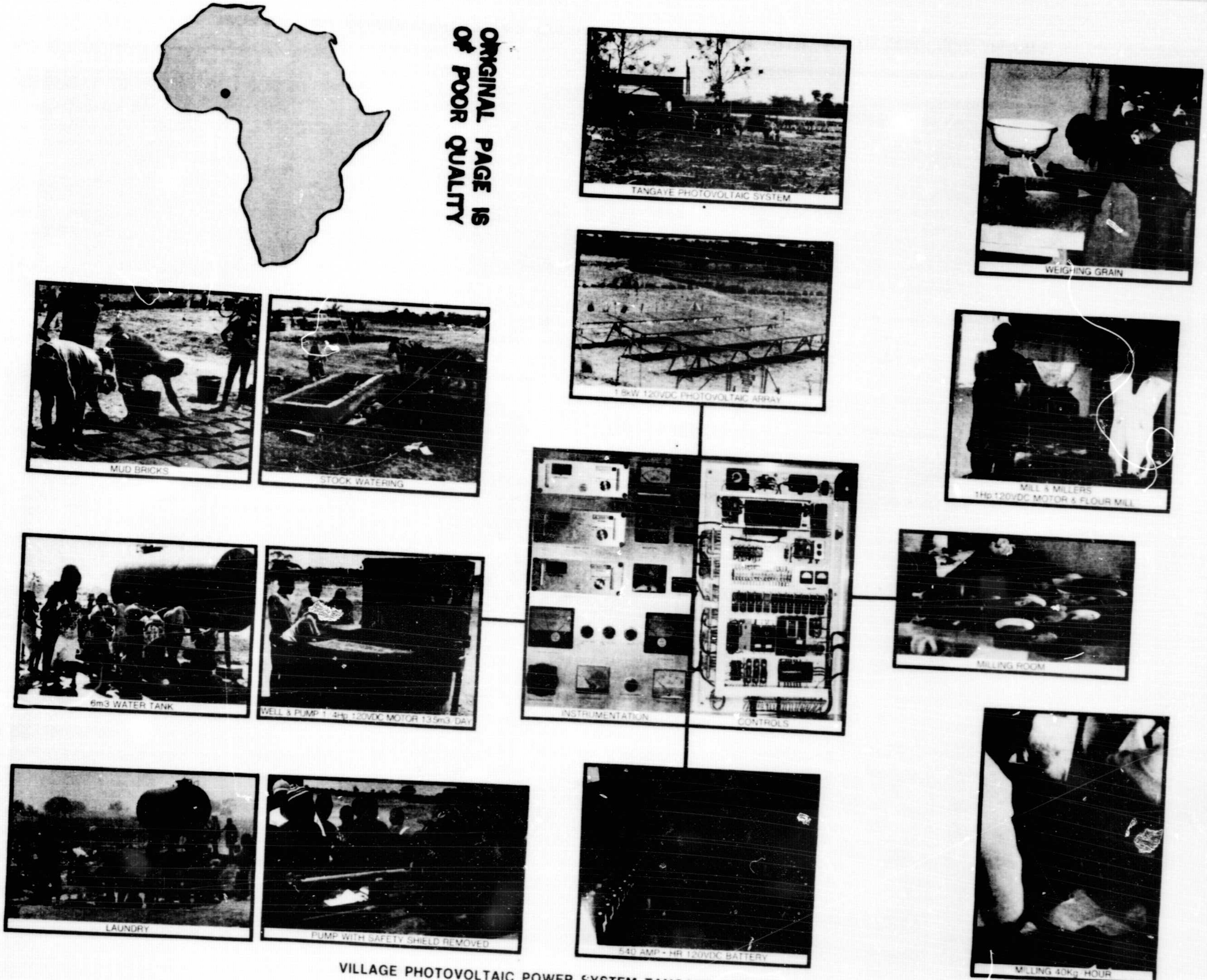
members and women coming to the Tangaye market ensure a steady work load at the mill. The installation has been the center of considerable interest and activity and the villagers are considering other enterprises for the area to further capitalize on the system.

These are the first photovoltaic systems designed to provide community electric power requirements. As such they are prototypes of systems which should find extensive application in developing countries throughout the world.



WORLD'S FIRST VILLAGE PHOTOVOLTAIC POWER SYSTEM - PAPAGO INDIAN VILLAGE OF SCHUCHULI, ARIZONA

Figure 1



VILLAGE PHOTOVOLTAIC POWER SYSTEM TANGAYE, UPPER VOLTA

Figure 2

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